Catalytic Production of Dimethylformamide from Supercritical Carbon Dioxide

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Received May 23, 1994

Many of the chemical substances produced from toxic carbon monoxide could be prepared more safely from carbon dioxide (CO_2), if only the catalytic efficiency of the reductions of CO_2 were enhanced and the cost of hydrogen were lower. It is our contention that the use of supercritical CO_2 ($scCO_2$) as both reaction medium and reactant[1-3] offers significant advantages for the activation of CO_2. $scCO_2$ is sufficiently liquid-like to allow the dissolution of many organic compounds[4] and some transition metal complexes,[1,5] while it is sufficiently gas-like to retain very high miscibility with other gases including hydrogen.[6] As a result, homogeneous catalysis in $scCO_2$ can be extremely efficient and rapid, especially for reactions which have both gaseous and organic components. Particularly appealing are reactions in which $scCO_2$ itself is one of the reactants. We now report a synthesis of *N*,*N*-dimethylformamide (DMF) from $scCO_2$ in which the catalytic efficiency is 2 orders of magnitude higher than any previously reported.

Formation of DMF from CO_2, H_2, and dimethylamine is only barely thermodynamically favorable at standard temperature and pressure, and in the actual synthesis, the equilibrium point is delicately determined by the reaction conditions. However, the reaction has proved to proceed smoothly under our conditions. Thus, in the presence of a catalytic amount of $RuCl_2[P(CH_3)_3]_4$ as a catalyst precursor, $scCO_2$ reacts with H_2 and dimethylamine to give DMF with up to 370 000 turnover numbers (TON, moles of product/mole of catalyst). Liquid dimethylammonium dimethylcarbamate is used as a source of dimethylamine for experimental convenience. Free dimethylamine gives the same results. The typical synthetic operation is as follows: a stainless steel reactor loaded with dimethylammonium dimethylcarbamate, $RuCl_2[P(CH_3)_3]_4$, and a stir bar was prewarmed to 100 °C under 40 atm of H_2. The pressure was increased to 80 atm with H_2 and then to a total of 210 atm with CO_2. After the required reaction time, the reactor was cooled first with cold water and then with an acetone/dry ice mixture. The hydrogen was vented and the reactor thawed, the CO_2 venting as it sublimed. The clean and high-yield synthesis of DMF was confirmed by ^1H NMR spectroscopy of an aliquot of the dried product mixture in $CDCl_3$.

A number of pioneering efforts were made on amide synthesis by homogeneous hydrogenation of CO_2 in the presence of amine in liquid solvents,[7] but the efficiency remained unsatisfactory. We find that the Ru-catalyzed DMF production from $scCO_2$ has particularly high catalytic efficiency. The conversion of dimethylamine was 99%, and this reaction displayed 99% selectivity for DMF. The product was contaminated with very small amounts of trimethylamine, an over-reduction product,[7f] and formic acid. An isolated yield of 62 000 TON was attained by running the reaction in a 150-mL vessel using dimethylammonium dimethylcarbamate (88 mmol) and $RuCl_2[P(CH_3)_3]_4$ (2.5 μmol) at 100 °C for 19 h. At much higher amounts of carbamate, H_2 becomes the limiting reactant; the highest yield obtained under these conditions is 370 000 TON in a 300-mL vessel. This value is far superior to the highest number, 3400 TON (72.5% yield), reported for DMF production from CO_2 in a liquid solvent.[7c,8] The use of a $scCO_2$-soluble catalyst is crucially important for this reaction.[1,2] In fact, the solubility of the Ru catalyst was confirmed qualitatively by passing a $scCO_2$ solution of the catalyst through a fine filter at 50 °C and 120 atm, and collecting the solid which precipitated at the vent.

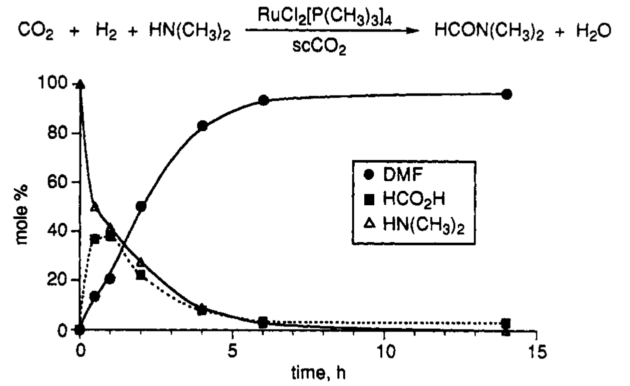

Figure 1. The composition of the product as a function of reaction time for the reaction of dimethylammonium dimethylcarbamate (5.0 mmol), H_2 (80 atm), and $scCO_2$ (130 atm) at 100 °C catalyzed by $RuCl_2[P(CH_3)_3]_4$ (2.5 μmol) in a 50-mL vessel.

The production of DMF from $scCO_2$ proceeds in two steps. The time–conversion curves in Figure 1 indicate that the fast Ru-catalyzed hydrogenation of CO_2 to formic acid (eq 1)[1,2] is followed by the slower thermal condensation of formic acid and dimethylamine (eq 2).[9] Under the reaction conditions, the dimethylammonium dimethylcarbamate is in an equilibrium with dimethylamine and CO_2.[10] Dimethylamine acts as a base to stabilize the formic acid in the first step and serves as a reactant in the second step.

$$CO_2 + H_2 \xrightarrow[\text{base}]{\text{Ru catalyst}} HCO_2H \quad (1)$$

$$HCO_2H + HN(CH_3)_2 \rightarrow HCON(CH_3)_2 + H_2O \quad (2)$$

The hydrogenation of $scCO_2$ to formic acid (eq 1) takes place very efficiently in $scCO_2$,[1,2] while the condensation step (eq 2) probably occurs in the liquid phase. The compositions of the liquid and supercritical phases change during the reaction (Figure

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(1) Jessop, P. G.; Ikariya, T.; Noyori, R. *Nature (London)* **1994**, *368*, 231–233.
(2) Ikariya, T.; Jessop, P. G.; Noyori, R. Jpn. Pat. Appl. 5.274721, 1993, Nov 4, 1993.
(3) Reetz, M. T.; Konen, W.; Strack, T. *Chimia* **1993**, *47*, 493.
(4) Bartle, K. D.; Clifford, A. A.; Jafar, S. A.; Shilstone, G. F. *J. Phys. Chem. Ref. Data* **1991**, *20*, 713–756.
(5) (a) Howdle, S. M.; Jobling, M.; Poliakoff, M. In *Supercritical Fluid Technology*; ACS Symposium Series 488; Bright, F. V., McNally, M. E. P., Eds.; American Chemical Society: Washington, DC, 1992; Chapter 10, pp 121–131. (b) Rathke, J. W.; Klingler, R. J.; Krause, T. R. *Organometallics* **1992**, *11*, 585–588. (c) Ashraf-Khorassani, M.; Hellgeth, J. W.; Taylor, L. T. *Anal. Chem.* **1987**, *59*, 2077–2081.
(6) (a) Kramer, G. M.; Leder, F. U.S. Patent 3 880 945, 1975. (b) Tsang, C. Y.; Streett, W. B. *Chem. Eng. Sci.* **1981**, 36, 993–1000. (c) Howdle, S. M.; Poliakoff, M. *J. Chem. Soc., Chem. Commun.* **1989**, 1099–1101. (d) Howdle, S. M.; Healy, M. A.; Poliakoff, M. *J. Am. Chem. Soc.* **1990**, *112*, 4808–4813.
(7) (a) Haynes, P.; Slaugh, L. H.; Kohnle, J. F. *Tetrahedron Lett.* **1970**, 365–368. (b) Kudo, K.; Phala, H.; Sugita, N.; Takezaki, Y. *Chem. Lett.* **1977**, 1495–1496. (c) Kiso, Y.; Saeki, K. Jpn Kokai Tokkyo Koho 77.36617, 1977; *Chem. Abstr.* **1977**, *87*, 84562s. (d) Phala, H.; Kudo, K.; Sugita, N. *Bull. Inst. Chem. Res., Kyoto Univ.* **1981**, *59*, 88–105. (e) Schreiner, S.; Yu, J. Y.; Vaska, L. *J. Chem. Soc., Chem. Commun.* **1988**, 602–603. (f) Schreiner, S.; Yu, J. Y.; Vaska, L. *Inorg. Chim. Acta* **1988**, *147*, 139–141. (g) Vaska, L.; Schreiner, S.; Felty, R. A.; Yu, J. Y. *J. Mol. Catal.* **1989**, *52*, L11–L16.
(8) The highest TON recorded in scientific journals was 1460 (% yield not stated) accomplished with $Pt_2[(C_6H_5)_2PCH_2CH_2P(C_6H_5)_2]_3$.[7f]
(9) Mitchell, J. A.; Reid, E. E. *J. Am. Chem. Soc.* **1931**, *53*, 1879–1883.
(10) (a) Wright, H. B.; Moore, M. B. *J. Am. Chem. Soc.* **1948**, *70*, 3865–3866. (b) Theodoropulos, S. Eur. Pat. Appl. EP 0 062 161 A1, 1982 and references therein.

0002-7863/94/1516-8851$04.50/0

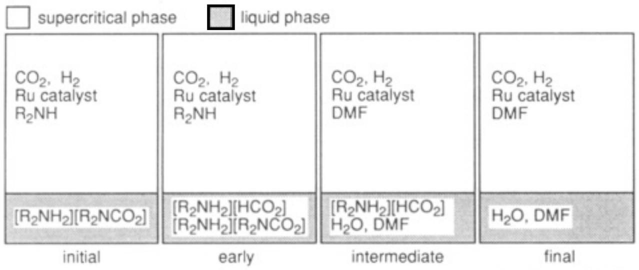

Figure 2. The composition of the phases during the reaction ($R = CH_3$). The size of the liquid phase is exaggerated; the relative volumes of the supercritical and liquid phases are 84:1 under the conditions of Figure 1 at the start of the reaction.

2). The published[6b] H_2/CO_2 binary mixture critical pressure and temperature were exceeded in these reactions. Thus the reaction mixture at the start consists of a homogeneous supercritical phase and the insoluble carbamate liquid. The dimethylammonium formate salt and water produced during the reaction are precipitated as a clear liquid. The amounts of liquid carbamate and formate salts decrease as the reactions of eqs 1 and 2 proceed. At the end of the reaction, the water is expected to be mostly in the liquid phase because of its low solubility in $scCO_2$,[4] while the DMF product could largely be present in $scCO_2$ in view of its complete miscibility with liquid CO_2.[11]

The catalytic efficiency of this synthesis for fixation of $scCO_2$ exceeds that of the related synthesis of formic acid from $scCO_2$, H_2, and $N(C_2H_5)_3$ with the same catalyst.[1,2] There are two major factors involved. Only small amounts of $N(C_2H_5)_3$, below the solubility limit in $scCO_2$, were used in the formic acid synthesis to avoid the possibility of forming a liquid amine phase in which the catalyst would dissolve.[1,2] For the DMF synthesis, there is no such restriction on the amount of carbamate charged.[12] In addition, the second, condensation, reaction (eq 2) produces water, which prevents the dissolution of the nonpolar Ru catalyst into the liquid phase, thereby keeping its high catalytic activity throughout the reaction.[12] This latter factor increases the efficiency of DMF production to near complete conversion even at high amine:catalyst ratios.

Compared to reported[7] liquid phase syntheses of DMF from CO_2, the new process is far more efficient. The key issue for the kinetic efficiency is the high rate of eq 1, which is primarily a result of the high H_2 concentration in $scCO_2$ as well as the lack of unnecessary molecular association around the Ru catalyst.[1] The combination of the two steps, eqs 1 and 2, in a one-pot procedure is also responsible for the high rate of DMF production; such high efficiency cannot be attained by the combination of the two separate synthetic operations, preparation of formic acid and dehydrative condensation of the acid and dimethylamine. Overall, these conditions for DMF synthesis are ideal.

The very high yield and rate of DMF production demonstrate that known homogeneously catalyzed reactions can be greatly increased in efficiency by the use of $scCO_2$ as the medium for its own fixation. With this improved catalytic efficiency and the lower toxicity of CO_2 compared to CO, the fixation of CO_2[13] with hydrogen and dimethylamine could become competitive with the carbonylation syntheses of DMF.[14]

(11) For the solubility of DMF and water in liquid CO_2, see: Francis, A. W. *J. Phys. Chem.* **1954**, *58*, 1099–1114.

(12) The Ru catalyst is insoluble in both dimethylammonium dimethylcarbamate and water.

(13) Pertinent reviews of the use of CO_2 as a C_1 chemical source: (a) Behr, A. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 661–678. (b) *Carbon Dioxide as a Source of Carbon*; Aresta, M.; Forti, G., Eds.; NATO ASI Series, Series C, 206; D. Reidel: Dordrecht, 1987. (c) Behr, A. *Carbon Dioxide Activation by Metal Complexes*; VCH: Weinheim, 1988.

(14) Bipp, H.; Kieczka, H. In *Ullmann's Encyclopedia of Industrial Chemistry*, 5th ed.; Elvers, B., Hawkins, S., Ravenscroft, M., Rounsaville, J. F., Schulz, G., Eds.; VCH: Weinheim, 1989; Vol. A12, pp 1–12.